ATMOS/ATLAS-3 Observations of Long-lived Tracers and Descent in the Antarctic Vortex in November 1994

M, C. Abrams[1], G. 1., Manney[2], M. R. Gunson[2], M. M. Abbas[3], A. Y. Chang[2], A. Goldman[4], F. W, Irion[5,2], H. A. Michelsen[6], M. J. Newchurch[7], C. P. Rinsland[8], R. J. Salawitch[2], G. P. Stiller[9], and R. Zander[10]

Abstract. Observations of the long-lived tracers N_2O, CH_4 and HF obtained by the Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument in early November 1994 arc used to estimate average descent rates during winter in the Antarctic polar vortex of 0.5 to 1.5 km/month in the lower stratosphere, and 2.5 to 3.5 km/month in the middle and upper stratosphere. Descent rates inferred from ATMOS tracer observations agree well with theoretical estimates obtained using radiative heating calculations. Air of mesospheric origin ($N_2O < 5$ ppbV) was observed at altitudes above about 25 km within the vortex. Strong horizontal gradients of tracer mixing ratios, the presence of mesospheric air in the vortex in early spring, and tbc variation with altitude of inferred descent rates indicate that the Antarctic vortex is highly isolated from midlatitudes throughout the winter from approximately 20 km to the stratopause. The 1994 Antarctic vortex remained well isolated between 20 and 30 km through at least mid-November.

introduction

The transport of long-lived tracers r-mains a focus of considerable interest, especially with the results from the Upper Atmosphere Research Satellite (UARS). *Schoeberl et al. [1995]* reexamined the issue with Halogen Occultation Experiment (HALOE) data (version 16) with a carefully developed identification scheme to classify profiles as inside or outside the vortex. Late winter descent rates of 1.5- 1.8 km/month in the lower stratosphere were obtained which arc consistent with theoretical analyses of meteorological data [*Rosenfield et al,, 1994; Manney et al., 1994].*

The ATMOS instrument is a Shuttle-borne high resolution Fourier transform spectrometer that obtains vertical profiles of atmospheric composition frnm solar occultation measurements of infrared atmospheric transmission [*Farmer*, 1987]. Observations that sample inside, outside, and across the edge of the polar vortex were made at high Southern latitudes (64-66°) during the ATLAS-3 mission (3 to 12 November 1994). In the present Letter, measurements of three long-lived tracers, N_2O, CH_4, and HF, are combined with potential vorticity (PV) from the United Kingdom Meteorological Office (UKMO) analyses to infer net winter descent rates. The results complement a similar analysis of descent rates within the NH polar vortex during the 1992/3 winter [*Abrams et al.*, 1995].

Revised: November 14, 1995

ATMOS and UKMO data analysis

N_2O, CH_4, and HF arc among more than 30 gaseous constituents that can be profiled from ATMOS spectra. The 1994 measurements provide a snapshot of the Antarctica vortex in early spring that shows the net effects of wintertime transport on the tracer distributions. The tracer measurements arc interpolated to isentropic (constant potential temperature, θ) surfaces, upon which passive tracers and PV arc conserved in the absence of diabatic and frictional effects. Figs.1 and 2 show the observed distributions of N_2O and CH_4 at 65 S as functions of θ and longitude. *Manney et al. [1996]* describe the degree to which the position of the vortex changes in relation to ATMOS measurements during this period: although its shape varies considerably, it is shifted off the pole i n the same direction throughout the mission, so measurements over the 10 days give a reasonable estimate of the longitudinal structure of the tracer fields. The strong correlation between the behavior of N_2O and CH_4, which arc fully independent measurements except for the common methodology used in the determination of pressure and temperature, demonstrates the consistency and accuracy of the ATMOS measurements. N_2O mixing ratios of about 5 ppbV and CH_4 mixing ratios of about 0.3 ppmv arc seen within the vortex down to near 600 K (about 25 km). These mixing ratios are typical of air with mesospheric origins.

Rossby-Ertel PV, obtained from the UKMO data assimilation system [*Swinbank and* 0 *'Neill,* 1994], can be used to characterize tbc location and extent of the polar vortex. PV is scaled [*Manney et al,* 1994] in 'vorticity units' to provide a modest range of 'sPV' values on surfaces of constant θ throughout the stratosphere. Strong horizontal sPV gradients coincide with the core of the polar night jet and represent a barrier to horizontal transport, facilitating the identification of the polar vortex edge. Contours of sPV arc overlaid in Figs.1 and 2.

The vortex edge is clearly indicated in Fig. 1 by very large gradients in N_2O and CH_4 at levels between about 420 and 1300 K. Up to about 1000 K, the strong tracer gradients arc coincident with large horizontal gradients in sPV. Theoretical studies have shown that coherent fragments of air with vortex-like tracer values may remain well after the final warming, and after the signature of the vortex in PV has disappeared [e.g., Hess, 1991]. The N_2O and CH_4 in Fig. 1 appear well-mixed below about 400 K. Although there arc strong sPV gradients below this level, they do not form until late winter [Manncy ct al., 1994], and arc not continuous around the circumference of the vortex [Manney et al., 1996]. I'bus, there is not expected to be as strong a barrier to transport at levels below 400 K. These strong N_2O and CH_4 gradients clearly demonstrate the extremely strong barrier to horizontal transport at the edge of the Antarctic polar vortex between 400 and 1100 K, and that this barrier remained intact in the lower stratosphere until at least mid-November 1994.

A vortex/extra-vortex classification scheme was developed which requires N_2O, CH_4, and sPV values on the 655 K isentropic surface all to be characteristic of the vortex (mixing ratios of less than 30 ppbv for N_2O and 0.60 ppmv for CH_4). Figs. 3-5 show mean vortex and extra vortex profiles of N_2O, CH_4 and HF. As was also apparent in Fig. 1, there is an obvious distinction between vortex and extra-vortex air between - 18 and 35 km.

Descent rates inferred from tracer profiles

Mean vortex and extra-vortex volume mixing ratio profiles of long-lived tracers measured in November 1994 (early spring) arc compared with early winter profiles from the ATLAS-2 mission (April 1993) in Figs. 3-5. The ATMOS measurements suggest minimal seasonal variation in the upper stratospheric profiles of long-lived tracers at midlatitudes (45-60 S) and that descent rates within the polar vortex can be assessed relative to either extra-vortex air that has not been within the polar vortex or to spring air prior to the onset of winter-time descent. In the Subsequent analysis, the former approach is used: comparison of vortex and extra-vortex profiles obtained during the same season (spring) and latitude, with corroboration from the opposite season extra-vortex profiles. An eight month period of descent (starting March 1) has been assumed in theoretical studies [*Fisher et al.*, 1993 and *Rosenfield et al.*, 1994]. However, the ATMOS measurements from the ATLAS-2 mission indicate that modest descent has occurred at altitudes above 35 km in early April, but not for lower altitudes; hence defining a single starting date for all altitudes is incorrect, Since descent in much of the high-latitude stratosphere begins shortly after the summer solstice [*Kiehl and Solomon,* 1986], well before the vortex forms, the relevant starting time for examination of unmixed descent is the date after which the polar vortex has developed to the extent of providing a significant barrier to transport. Before this tire, any signature of descent would be lost duc to unrestrained horizontal mixing. To estimate this date, wc examined the time evolution of sPV gradients as a function of sPV, during the SH fall of 1994, at levels throughout the stratosphere canal located the first date on which sPV gradients associated with the polar vortex were significantly stronger than in surrounding regions. This leads to starting dates, given in Table 1, ranging from 25 March 1994 in the upper stratosphere to 12 May 1994 in the lower stratosphere.

Mean descent rates are determined from spring vortex and extra-vorlcx profiles of tracers assuming unmixed vertical descent within the vortex (i.e., vertical motion is the only factor that alters the profiles of]ong-lived tracers,), and that extra-vortex profiles arc representative of fall conditions. For each of the three long-lived tracers, the descent rate (Adj. Rate, in the table) has been inferred by dividing the vertical distance between the inside and outside profiles at similar gas amounts (Δz in Table 1) by the time period of descent, based on starting dates derived from the evolution ofsPV (St. Date in l'able 1). Descent rates assuming an eight month period of descent are also given in Table 1 (Rate), Descent rates for each of the tracers, given in Figure 6, are in good agreement given the precisions of the measurements. The unweighted standard deviations arc between 10 and 25%, and the precision of the vertical registration ranges between 0.05 km (at 20 km) and 0.4 km (at 50 km) are in relatively good agreement with the scatter between the rates inferred from each of the three gases. Air initially at 20 km descended 0.6 km/month, while air initially at 30 km descended 1.5 km/month. Air in the lower mesosphere at initial heights above 50 km descended 3.3-3.5 km/month to levels around 600 K (approximately 20-25 hPa). The curvature of the descent rate profiles inferred from ATMOS measurements of N_2O, CH_4 and HF provides additional corroborative evidence for a highly isolated vortex throughout the winter, during periods of rapid loss of O_3, H_2O and nitrogen oxides within the vortex. in 1994, the vortex remained strong and isolated between about 20 and 30 km until at least mid November. Therefore, at these levels, polar processes arc not expected to have any strong direct impact on mid-latitude distributions of O_3, H_2O and nitrogen oxides until later in the spring

Rosenfield et al., [1994] calculated diabatic descent rates using NMC temperatures during the 1992 SH winter, and found average winter (March-October) descent rates of 0.4-0.9 km/month for air starting in the lower stratosphere, and 3.3 -3.6 km/month for air started at 52 km. This profile is shown in Fig. 6. Rosenfield noted the paucity of information on descent rates inferred from tracer profiles in comparison with column measurements indicating 6-8 km of subsidence above 12 km [*Toon et* al., 1989]. Ground-based measurements of N_2O [*Crewell* et *al.* 1995] at the South pole were used to derive early winter, late winter, and net winter descent rates. The net winter descent rates of *Crewell et al., [1995]* compare favorably with tbc present results. Analysis of UARS/HALOE satellite measurements [*Schoeberl et al., 1995]* yielded descent rates of 1.5- 1.8 km/month for the lower stratosphere (altitude below 2S km), during September and October and a net winter descent rate of 1.5 km/month. These descent rates agree closely with the present measurements and tbc theoretical calculations of *Rosenfield et al., [* 1994].

The estimates from ATMOS presented here constitute minimum estimate of descent rates, since horizontal mixing will dilute the signature of unmixed descent in the vortex. This is expected to influence our results most at the highest and lowest levels, where there is evidence of significant horizontal mixing. Similarly, seasonal variation in the extra-vortex tracer levels, or mixing gradients at the vortex edge, and averaging over the entire season prior to the measurement period would compound the under-estimation of the descent rates, The descent rates for late winter [*Schoeberl et al.,* 1995 and *Crewell et al., 1995]* are 2-3 times larger than the net rates, Given tbc differences between the measurement years (Toon - 1987, Crewell - 1993, Schoeberl -1992, and 1994 in the present work) , periods, and durations, the results arc remarkably consistent, The ATMOS measurements extend the altitude range of descent measurements up to the lower mesosphere and provide definitive evidence of transport of mesospheric air to levels near 25 km,

Conclusions

Colocated measurements of the long-lived tracers N_2O, CH_4, and HF during the ATMOS/ATLAS-3 mission provide conclusive evidence for descent within the vortex of air originating in the lower mesosphere to about 25 km over the course of the winter.

Descent rates of 0.5- 1.5 km/month in the lower stratosphere (below -30 km, 850 K, or 10 hPa) , and 2. S-3.5 km/month in the upper stratosphere and lower mesosphere arc inferred from the tracer measurements. The consistency of the descent rates inferred from profiles of three long-lived tracers attests to the precision of the measurements and the robustness of the overall conclusions. Our results arc consistent with previous theoretical and observational estimates of descent, but extend the vertical range of descent estimate from observations. Strong horizontal gradients in N_2O, CH_4, and 1 IF demonstrate the vortex was highly isolated from mid-latitude air, between 20 and 30 km, until mid-November.

Acknowledgments. Wc thank the UKMO for providing meteorological data. Research al tbc Jet Propulsion laboratory (JPL), California Institute of Technology, is performed under contract to the National Aeronautics and Space Administration (NASA). Research at the University of Liège was partially supported by the Belgian Global Change Program through the SSTC, Brussels.

References

Abrams, M. C. e/ *al.*, Trace gas transport in rhc Arctic vortex inferred from ATMOS ATLAS-2 observations during April 1993, *Geophys. Res. Lett., this* issue, 1996.

Crewell, S., D. Cheng, R. L. dc Zafra, C. Trimblc, Millimlcr-wave spectroscopic measurements over the South Pole, 1: a study of stratospheric dynamics using NIO observations, *J. Geophys. Res., in* press, 199S.

Fanner, C. B., High resolution infrared spectroscopy of the Srrn and the Earth's atmosphere from space, *Mikrochim. Acta (Wien), Ill,* 189-214, 1987.

Fisher, J., A. O'Neill, and R. Sutton, Rapid descent of mesospheric air in the stratospheric polar vortex, *Geophys. Res. Lett.*, 20, 1267-1270, 1993.

Hess, P. G., Mixing processes following the final stratospheric warming, *J. Atmos. Sri.*, 48, 1625-1641, 1991.

Kiehl, J. 1'. and Solomon, S. , On the radiative balance of the stratosphere, *J. Atoms. Sci.*, 43, 1525-1534, 1986.

Manncy, G. L., R. W. Zurek, A. O'Neill, and R. Swinbank, On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, 51, 2973-2994, 1994.

Manney, G. L., R. Swinbank, and A. O'Neill, Stratospheric meteorological conditions for the 3-12 Nov. 1994 A' MO S/ATLAS-3 measurements, *Geophys. Res. Lett.*, this issue, 1996.

Rosenfield, J. E., P. A. Newman, and M. R. Schoeberl, Computations of diabatic descent in the stratospheric polar vortex, *J. Geophys. Res.*, 99, 16677-16689, 1994.

Schoeberl, M. R., L. Mingzhao, and J. E. Rosenfield, An analysis of the Antarctic Halogen Occultation Experiment trace gas observations, *J. Geophys. Res.*, 100, 5159.5172, 1995.

Swinbank, R, and A. O'Neill, A stratosphere-troposphere data assimilation system, *Mon Weather, Rev., 122,686-702,* 1994.

Toon, G. C., C. B. Farmer, L. L. Lowcs, P. W. Schaper, J.-F. Blavier, and R. H. Norton, Infrared aircraft measurements of stratospheric composition over Antarctica during September 1987, *J. Geophys. Res.*, 94,16571-16596, 1989.

M. C. Abram (m.c.abrams@larc.nasa. gov), Aerosol Research Branch/Atmospheric Sciences Division MS-475, NASA Langley Research Center, Hampton, VA, 23681, USA

Figure Captions

Figure 1. Potential temperature/longitude cross-section at 65° S of N_2O (color) and sPV (contours). The vortex region is clearly defined by the steep gradients in potential vorticity between -1.2 and -1.6x 10-4 sec^{-1} in the lower stratosphere between -200° and 350° E.

Figure 2. Potential temperature/longitude cross-section at 65° S of CH_4 (color) and sPV (contours). Note that the CH_4 and N_2O maps do not display a gradient below 4S0 K, whereas there is a significant gradient in sPV.

Figure 3. Mean N_2O volume mixing ratio profiles.

Figure 4. Mean CH_4 volume mixing ratio profiles,

Figure 5. Mean HF volume mixing ratio profiles.

Figure 6. Adjusted descent rates obtained from ATMOS trace gas measurements compared with previous observations and theoretical calculations. 'fable. 1 enumerates the starting dates used to adjust the descent rates. For comparison the rate of 1 km/month at 24 km corresponds to 32.9 m/day, or 0.039 cm/sec, assuming *365.25/12 = 30.44* days/month.

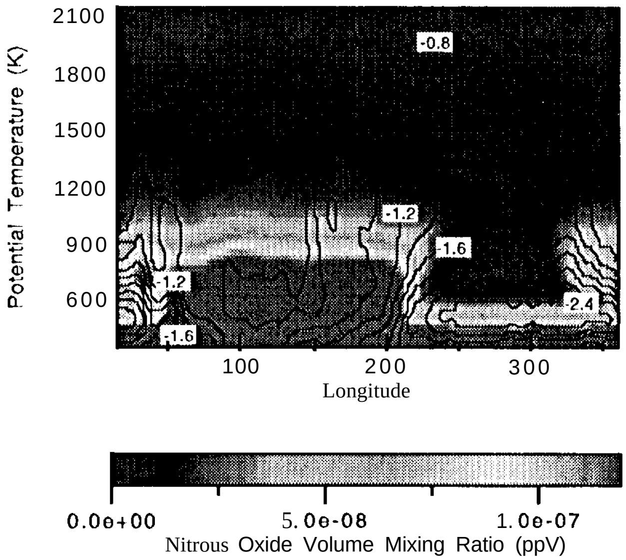

Figure 1.

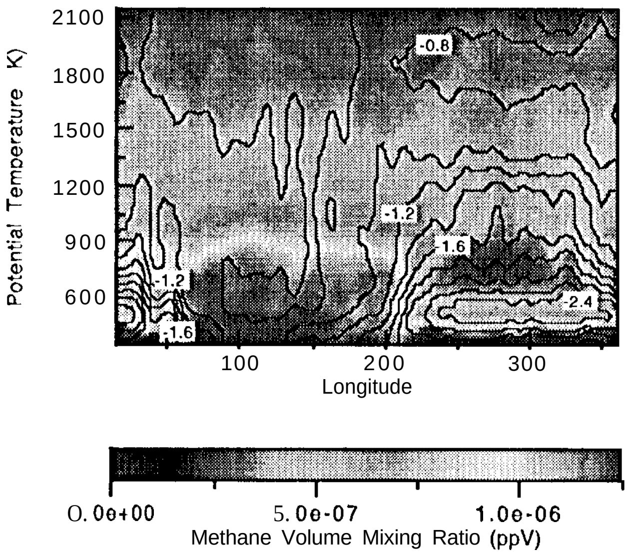

Figure 2.

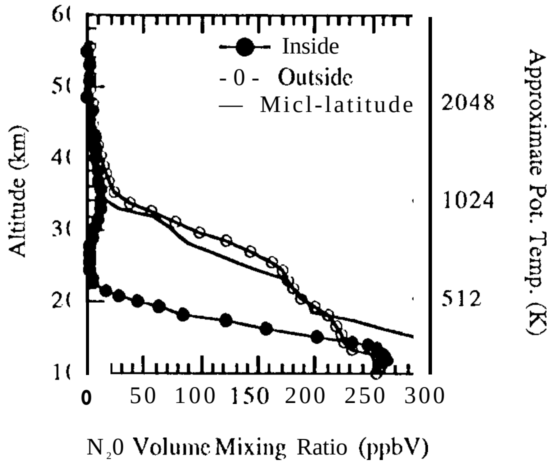

Figure 3.

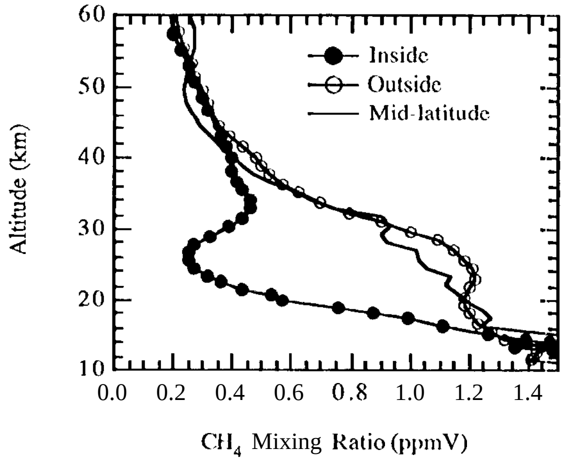

Figure 4.

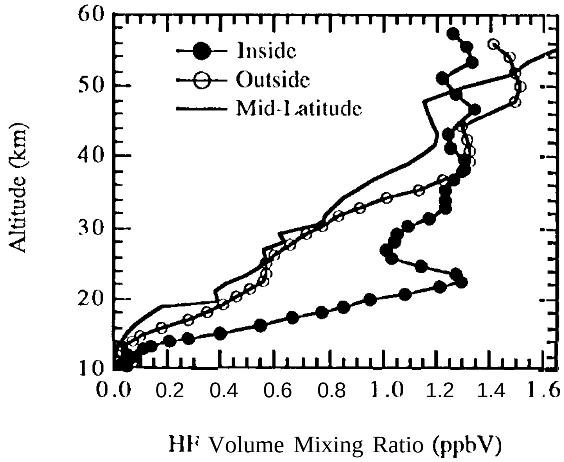

Figure 5.

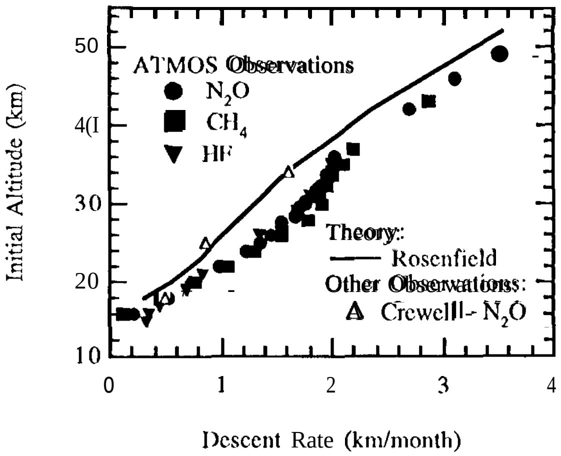

Figure 6.

Table 1: ATMOS/ATLAS-3 Antarctic Net Descent Rates

St. Alt. (km)	St, θ (K)	Δz (km)	Rate (km/mo)	St. Date (dd/mm)	Adj. Rate (km/mo)
50	1700	26	3.25	25 Mar	3.6
42	1300	20	2.5	25 Mar	2.7
34	960	14.4	1.8	1 Apr	2.1
30	840	12.0	1.5	5 Apr	1.8
24	655	8.4	1.05	15 Apr	1.3
20	520	4.4	0.55	8 May	0.8
17	465	2.4	0.3	12 May	0.4
15	425	1.4	0.18	*	----

*at 425 K the starting date is uncertain, but much later.